Planetary Missions Enabled by Space Nuclear Power

~~ROBOTIC PLANETARY MISSION BENEFITS ENABLED~~ OR ENHANCED BY NUCLEAR ELECTRIC PROPULSION

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ABSTRACT

Several inte.resting planetary missions are either enabled or significantly enhanced by nuclear electric propulsion (NEP) in the 50 to 100 kW power range. These missions include a Pluto Orbiter/Probe with an 11-year flight time and several years of operational life in orbit versus a ballistic very fast (13 km/s) flyby which would take longer to get to Pluto and would have a very short time to observe. the planet. (A ballistic orbiter would take about 40 years to get to Pluto.) Other missions include a Neptune Orbiter/1'robe, a Jupiter Grand Tour orbiting each of the major moons in order, a Uranus (lbiterfl'robe, a Multiple Mainbelt Asteroid Rendezvous orbiting six selected asteroids, and a Comet Nucleus Sample, Return. "l'his paper discusses potential missions and compares the nuclear electric propulsion option to the conventional ballistic approach on a parametric basis.

1. INTRODUCTION

Planetary missions using nuclear electric propulsion (NEP) have been subjects of study for two or three decades. They have not been seriously considered by mission planners, however, because of the unavailability of the required technologies ancl because there were. plenty of ballistic missions of interest. Further, until recently, the mission planners concentrated on next-generation missions, with a few years until the mission start, leaving too little time to influence significant technology development. This situation hact the added disbenefit of depriving the technology developers of the user advocacy necessary to acquire sufficient funds for robust technology programs.

With improvements occurring in all of. these circumstances, this study was initiated with joint funding from the planetary mission "user community" in the Office of Space Science and

Application (OSSA) and the Office of Aeronautics and Space Technology (OAST) of the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE). The focus is on the second major mission opportunity (early ?000s) rather than the next one (late 1990s), allowing time for the results to offer technology definition, advocacy, and development prior to a mission start.

The study objectives were designed to provide answers to the following questions:

- How necessary and how well is NEP able to help execute the missions envisioned by the OSSA mission strategists for 2.000 to 2.010 new starts?
- What can NEP technology of Year 2.000 do for a roster of missions considered as potential candidates (Ref. 1)?
- What kind of an NEP system is needed to perform a mission satisfying, at a minimum, the fundamental science objectives mandated by OSSA?
- How much resiliency can a mission have relative to technology uncertainties?
- What are the implications of these NEP missions to the NASA launch system and other elements of space missions?

2. DISCUSSION

Six missions were studied in detail, conducting parametric low-thrust mission performance analyses and iterating, results with technology teams at both the Jet Propulsion Laboratory (JPL) and the Lewis Research Center (LeRC):

Neptune Orbiter/Probe (NEO/P)
Pluto Orbiter/Probe (PLO/P)
Jupiter Grand Tour (JGT)
Uranus Orbiter/Probe (UO/P)
Multiple Mainbelt Asteroid Rendezvous (MMBAR)
Comet Nucleus Sample Return (CNSR)

NEP mission concepts (science goals and mission scenarios) are constructed from the current ballistic mission concepts with the addition Of various improvements readily perceived to be possible with NEP (Ref. 2). The improvements include more payload, better mission/science scenarios, more frequent launch opportunities, and shorter flight times, It is clear that the availability of high power aboard the spacecraft can change the characteristics of these missions in more ways. It can change the types and designs of science instruments and experiments in more. fundamental ways due to the added on-board power, computing capability, and communication rates. These beneficial effects have yet to be explored.

Nuclear power was assumed to be supplied by SP-100 derivative technology (Ref. 3) projected to be available in the year 2000. The characteristics of the baseline. SP-100 technology adapted for interplanetary missions are shown in Table 1. Other reactor system technology improvements are expected to further reduce the power system mass. NASA advanced technology program goals include improving the thermoelectric material figure-of-merit (Z) from 0.85 x 10^{-3}/K to 1.4, and decreasing the radiator density from 8.74 kg/m^2 to 5.5. The mass versus power is shown in Fig. 1.

2..1 Thrust Subsystem Architecture

For high power NEP mission applications, a cluster of 30 cm thrusters (see Fig. 2) configured to function as one unit from a single processor unit has been proposed by Brophy (Ref. 4). The functionality of this engine is indistinguishable from that of a more conventional engine configuration except that there are multiple hollow cathodes to be controlled hem. The number of thrusters clustered to operate as a unit is varied according to the specific impulse and power level required for the mission. The number of cluster units installed is determined by the total thrust burn time requirement of the mission and the level of redundancy intended. Since no useful reliability data exists, the redundancy is provided arbitrarily in the form of a 25% margin in thruster operating life.

As a ground rule for the analysis, the installation of two power processing units (PPUs), the second as a standby, is assumed. This is regarded as appropriate because the predicted operating life. of the PPU is much longer (5-15 years) than the thruster.

2.2 Thruster Performance Characteristics

Conservatively projected performance of the 30-cm thruster as a function of specific impulse is characterized in Table 2. with krypton as the propellant. The total efficiency depicted in Table 2 includes the PPU operating at 93%, efficiency. The predicted lifetime is 1(),0()0 hours.

3. RESULTS

Mission performance characteristics for each of the six types of missions are given parametrically in Tables 3 through 8, including key comments cm the results. The use of NEP with two classes of launch vehicles, Titan IV/Centaur and Heavy Lift launch Vehicle (HLV) with Centaur upper stage, are considered. Titan IV/Centaur is the largest launcher currently available. The capability of the Shuttle-C/Centaur, which was under development until 1991, is used to represent a future heavy launcher expected from the U.S. National Launch System Development Program. Not all the missions can be attractively preformed with the (Titan IV/Centaur + NEP) combination; only those deemed attractive are presented in the tables.

NEP capability, requirements, and key improvements over ballistic missions are discussed.

3.1 Uranus Orbiter/Probe

The science objectives of the Uranus mission include studies of the Uranus atmosphere and its satellites and ring systems. Only a very preliminary ballistic mission concept considers an Earth-Jupiter gravity assist trajectory and takes 15 years to math Uranus. After delivering a Uranus probe, the spacecraft makes all Observations from a loose elliptic orbit, The science return is restricted mostly to distant flybys of satellites and observations of atmosphere and rings. The mission dependence on Jupiter gravity assists results in sparse mission opportunities.

The NEP mission scenario is far more rewarding scientifically. Upon arrival, the NEP spacecraft spirals gradually into the vicinity of the planet to about five. Uranus radii. in the process, the NEP spacecraft releases an atmospheric probe, performs the relay link, and subsequently rendezvous with each of the outer five moons (which vary in radius from 320 to 1010 km). In short NEP offers the grand tour of Uranus satellites and rings and delivers an atmospheric probe.

This mission is not attainable with (Titan/Centaur + NEP) within an attractive flight time. It is feasible with a (HLV/Centaur + NEP) system anti it can be performed satisfactorily in 10.5 to 14 years with a comfortable performance margin.

3.? Neptune Orbiter/Probe

The fundamental mission objectives of NEO/P are 1) to characterize the structure, composition, and dynamics of Neptune's atmosphere; 2.) to study the geology, surface composition, atmosphere, and atmosphere- surface interactions of Triton; 3) to study the geology and composition of other satellites; and 4) to determine the nature, composition, and dynamics of the ring system and the interaction of the ring material with Neptune's magnetosphere.

The problematic aspect of the current chemical mission concept is the long flight time; ≥18 years, The orbital design at Neptune is also severely restricted by the on-board AV capability of a Mariner Mark II (MMK II) spacecraft. Like Galileo and Cassini, the orbital sequences are built around satellite (Triton) gravity assists to save AV and acquire Triton science at each of the many (≈ 45) swingbys. The flyby speed of Triton is 4 to 5 km/s. The viable mission opportunities are very few because the, occurrence of a favorable planetary (Earth, Venus, and Jupiter) alignment is rare. Typically, a good launch opportunity involving a Jupiter swingby is available for about two consecutive years, but after that, a favorable Jupiter-Neptune alignment will not recur for about another 13 years.

The proposed NEP mission consists of the deliver-y of a spacecraft to orbit about Neptune and Triton, the delivery of a probe into the planet's atmosphere, and fast flybys of Neptune's small satellites and ring systems. If a sufficient performance margin exists, the option of a Triton lander may be considered. Using (HLV/Centaur + NEP), a 1400-kg orbiter with a 376 kg atmospheric probe and a small (50 kg) Triton lander can be delivered to Neptune in 12 years.

3.3 Pluto Orbiter/Probe

Pluto is the last of the major planets yet to be explored with a spacecraft. The proposed chemical option uses a 2.001 Earth-Jupiter gravity-assist trajectory (13-15 year trip) and briefly encounters the Pluto-Charon system at a flyby speed of about 13 km/s. Because of the weak gravity of Pluto, an orbiter or even a slow flyby is extremely difficult using a ballistic mode unless a very long flight time., approaching 40 years, is acceptable.

The science goals for this mission are 1) to study the geology, internal structure, surface composition, and atmosphere-surface interactions on Pluto; 2) to map the surface composition and geology of Charon, and to determine whether surface processes or geologic features may have resulted from gravitational interactions between Pluto and Charon; 3) to determine the dynamics and composition of Pluto's atmosphere before atmospheric collapse (between 2020 and 202 S); and 4) to conduct in-situ science with probes/soft landers cm Pluto anti Charon.

The very weak gravitational pull of Pluto is an attractive feature for the NEP mission design. At the arrival of an NEP spacecraft with a $V_\infty = 0$, a rendezvous state is nearly achieved and will require only a modest amount of AV to explore both Pluto and Charon. A rendezvous mission with Charon comes first before the spacecraft spirals into a tight orbit about Pluto. Performance permitting, a lander may be deployed at both bodies. A lander can provide in-situ measurements of the surface as well as the atmosphere during its descent.

With a (Titan IV/Centaur i- NEP) an orbiter mission to Pluto and Charon (no probes) is feasible with a 14.5-year trip. 1 lowever the performance margin is not large, (a mission may tolerate ~15% of NEP system mass uncertainty, if the flight time is increased to 16.5 years) and the probe may not be accommodated. If the. mass growth of the total flight system can be controlled and after considering the impacts of all potential complications anticipated in an NEP mission, this may be an early NEP mission candidate. The reasons for an early application of NEP on PLO are]) the science content of the mission is greatly improved over the ballistic counterpart, orbiter vs fast flyby; 2.) it appeal-s to be feasible with the currently available launch vehicle; 3) the trip time. is comparable to the ballistic flyby mission (1 3-15 years) and not too objectionable; and 4) there is a need for arriving at Pluto before 2020-2025.

With an (HLV/Centaur + NEP) a much faster trip time of an 11.5-year (without probes) mission is feasible., An additional year of flight time allows the delivery of a 4 14-kg lander to Pluto or Charon. With a 13.5-year flight a lander on both can be accommodated. A reasonable per-for mance margin exists.

3.4 Jupiter Grand Tour

The "Jupiter Grand Tour" is a mission concept especially made for NEP in which the objective of orbiter observations of four Galilean satellites is to be realized in a single launch. A satellite orbiter riding on NEP is to successively orbit about Callisto, Ganymede, and Europa and potentially 10 (if the radiation problem can be managed). Additional rendezvous or slow encounters of this spacecraft with other satellites arc also expected. A more ambitious concept includes the addition of Jovian space physics exploration (Jupiter Polar Orbiter mission = JPO) involving two fields and particles spacecraft. This option is not set as the primary mission goal in this study, but in cases where an excess performance margin exists, additional landers or JPO spacecraft arc considered.

If we were to contemplate a mission providing equivalent science using a chemical option, it would probably require five Titan IV/Centaur launches over a period of many years; four for the Galilean orbiters anti one for J] '(I- 1 and JPO-2.

Although the performance margin is not too large (- 10%), an orbiter class tour of all satellites (no probes) is feasible using a (Titan IV/Centaur + NEP). The flight time is 5 to 6.5 years. This trip time is probably acceptable, considering the significant amount of science return expected. If an (HLV/Centaur -t NEP) is used, the tour of all satellites is feasible with a flight time of 3.5 years. However, noting the rapid growth in the payload capability with the longer flight time, longer flight time options may be preferable. The addition of two -1000 kg landers for two of the Galilean satellites or addition of two small fields and particles spacecraft (2.500 kg total) arc possible by choosing a longer 5-6 year trajectory.

3.5 Multiple Mainbelt Asteroid Rendezvous Mission

The science goals for an asteroid mission are to determine the asteroid size, shape, rotation, albedo, mass, density, surface morphology, surface composition, magnetic fields, and interaction with the solar wind, Since the asteroid population is diverse (in size, physical and compositional characteristics, and their distance from the sun), a scientifically meaningful asteroid mission would require sampling of a sufficiently large number of diverse classes of asteroids. This is the overriding requirement imposed by the asteroid science community for the design of an MMBAR mission.

In a ballistic option using the. combination of a Titan IV/Centaur and MMK 11 spacecraft, at the maximum, two asteroid rendezvous can be attained. This probably will involve double swingbys of Mars and take about eight years to attain. The capability of a chemical propulsion system also limits the encounters to asteroids residing only in the innermost asteroid belt.

NEP with its large AV capability offers the opportunity to not only capture more targets, but also selective targets of interest. Vesta and Ceres are two asteroids most frequently mentioned as desirable targets. As an example, to demonstrate the potential of NEP in performing an MMBAR mission, a rendezvous sequence built around these asteroids is considered in this study. The proposed NEP mission concept consists of sending one orbiter spacecraft and, optionally, a number of landers or penetrators. The spacecraft will observe an asteroid for a nominal duration ($\approx$ 60 days minimum) from a rendezvous state ($\approx$ 0 relative velocity) and then move cm to the next target.

It is indicated that a mission involving six highly desirable targets is made in 13.5 years and is within the reach of a (Titan 1 V/Centaur + NEP) system. Although onl y a small performance cushion is indicated in Table 7, there are a number of ways that are available to maintain the viability of this mission, such as change of targets, longer flight time, or even reducing the number of targets. Note also that flybys of asteroids of opportunity are available to further enhance the science return. This is perhaps the best choice for the first NEP mission because it uses an available launch vehicle; the first asteroid data is expected about 2 years after launch; anti it is resilient to errors due to preflight mass growth or inflight performance degradations. One can continue with the mission at a slower pace and choose alternate targets as it proceeds. Given an (III .V/Centaur + NEP), MMBAR can be accomplished in a slightly shorter flight time compared to the case! when a Titan IV/Centaur is used. However, no significant increase in payload margin is observed. The indication is that shortening the flight time beyond the natural boundary or aiming for hard-to-access targets because they are more desirable are accompanied by a stiff performance penalty. The natural transfer time between asteroids is about half tbc orbital period of tile asteroids, i.e.., 1,5 years in the inner belt to 2..5 years in tbc mici-belt. On the average, 2 years pcr target is expected.

3.6 Comet Nucleus Sample Return

The primary objective of a CNSR mission is to return to Earth pristine samples of comet surface material, core material, and volatiles.

Ballistic CNSR performance possibilities have been studied quite extensively by Sauer (Ref.5). A lack of opportunity to access desirable targets appears to be the main drawback. The capability of the presently available Titan IV/Centaur is such that a mission is possible only with multiple gravity assists of Venus and Earth, resulting in flight times of 8.5 to 10.5 years. If an HLV/Centaur class launch vehicle becomes available, CNSR missions to a few relatively easily accessible comets are possible using a ΔV-EGA trajectory with a typical round trip time of 7 to 8 years.

One NEP version of the mission may be as follows: 1) NEP, a main spacecraft, a lander-sampler, and an Earth-return capsule (aerocapsule) will be sent to rendezvous with a cicsil-able (relatively active/new) comet; 2) the main spacecraft is used for round trip guidance, control, command, and communications; it also performs the high resolution imaging needed for site selection; 3) the main spacecraft remains with NEP; 4) the lander vehicle with the Earth-return aerocapsule lands on the comet and collects samples, the lander will be left on the comet; 5) the acquired samples and Earth-return capsule are designed to ascend from the comet and dock with the main spacecraft to travel back to Earth using NEP; 6) upon arrival at Earth the sample. capsule may be released for direct atmospheric entry or captured via on-orbit recovery. One anticipated benefit of NEP is to gain frequent opportunity to access a greater number of comets of interest (active, fresh comets). Additionally, the preservation of the sample during the return trip is made easier with the ample power of NEP. If direct-Earth entry can be avoided with an on-orbit recovery, NEP will be helpful in attaining the key science goal of "pristine. sample preservation" by not subjecting the sample to the high shock environment of a direct-Earth entry.

An acceptable mission with (HLV/Centaur + NEP) will require a flight time of 6.7 to 7.6 years for the examples used. This is associated with a class of trajectory (called indirect, see Fig. 8) requiring about 1.5 revolutions about the sun in going to the comet. No significant performance margin is indicated. An additional margin, if needed, will require another class of indirect trajectory involving 1.5 rev about the sun for both the outbound and the inbound legs and would take nearly two years longer-. The NEP system requirement for (his mission is different from the other NEP missions. The Isp is relatively low (<5000 seconds), and the thrust time is short; ~4 years compared to other missions. The reason for the above behavior can be attributed to the eccentric nature of the comet orbit.

4. NEP PARAMETRIX SUMMARY

Based upon the performance assessment made above, the delineation of NEP system design parameters best suited for various missions is made and summarized in "Table 9. A range of parameters rather than a single design point is provided. The first entry corresponds to the shortest flight time (except for JGT) and the nominal design point. The second entry represents a design point if the worst (but tolerable) fall back position is taken.

Given an HLV/Centaur launch vehicle, all missions can be performed with a 100-kW space reactor power system (SRPS). The nominal (full-power, life-time) capability of about (8,15) years satisfies the requirements of all *nominal* missions. The thrusters should be operating at about 8000 seconds for JGT and outer planetary missions. Isp for MMBAR and CNSR are low, 5000 to 6000 seconds. The thrust subsystem entails fifty to seventy 30-cm thrusters (ion sources) depending on the mission. If the nominal NEP mass characteristics are not met, longer thrust times, longer life times and more thrusters are implied to further compound the design problems.

To do the MMBAR, PLO, and JGT missions with a Titan IV/Centaur, the optima] power level of SRPS is about 40-60 kW. A full power time of 8 years is acceptable but the long mission time for PLO dictates a lifetime of 15 to 16 years. The number of thrusters involved is about 40 maximum.

The design parameters suggested above represent a "near optimal" set of design parameters. The characteristics of low thrust mission performance are such that the performance degradation is not severe as one deviates from these design points. If some design parameters are difficult to meet, the, imposition of a constraint is a possibility. The degradation in performance due to a constraint, e.g. thrust time, can be made up easily with re-optimized Isp, P0, or FT etc. as long as the constraint is not drastically different from the optimal value.

5. TRAJECTORIES

An example heliocentric trajectory for each mission is provided in Figures 3 through 8. "Thrust-coast-thrust" is the common thrust profile, needed for rendezvous and $V_\infty = 0$ planetary encounter trajectories. Due to the low level of NEP thrust and the. near zero Earth escape energy, the spacecraft needs to spiral about the sun for a while to gather enough energy to head towards the outer planets. Note that a scenario with many thrust on-off cycles is involved in the MMBAR mission. Although no actual planetary phase thrust profile can be generated at present, multiple encounters with satellites (e. g., JGT) would dictate the same type of requirements.

6. CONCLUSIONS

The applicability, benefits, and requirements of NEP for a set of important solar system exploration missions have been examined assuming conservative projections of current SP-100 based space nuclear power technology and 30-cm ring-cusp thruster technology with the expectation that the first NEP mission may be launched in the year -2005 (Program New Start year 2000).

6.1 NEP Performance/Requirements

It can be conducted that all of the missions can be pm-formed with reasonable confidence (i.e., a tolerance for an NEP system mass uncertainty of ~30%) if a heavy lift launch vehicle with the capability of a Shuttle C/Centaur or better becomes available, The SRPS power level of 100 kW can accommodate all missions. The mass characteristic of the nominal dry NEP system is a specific mass of -57 kg/kW. The assumed thruster life is 10,000 hours with a margin of 25% (effectively 7500 hours).

Given a Titan IV/Centaur and about a 50-kW NEP system, it is possible to perform missions MMBAR, PLO, and JGT, although the performance margins are relatively small (-15%). These missions may be a natural choice for early NEP applications.

6.2 Mission Improvements Over Ballistic Options

In addition to far better science, NEP is able to remove most of the perceived difficulties and dilemmas of the missions associated with current MMK 11 derived ballistic approaches, specifically: 1) NEP enables a Pluto orbiter mission; 2.) it provides shorter flight times for Uranus (1 0.5 years vs 15 years), Neptune (12- 15 years vs >18 years), and Pluto (1 1.5-15 years vs -40 years for an orbiter mission); 3) it allows for orbiter missions to the major satellites of Jupiter, Uranus, Neptune, anti Pluto vs flybys; 4) it enables a multiple. body mission in the Jupiter Grand Tour and Uranus Olbiter/Probe with one launch and a multiple asteroid-of-c}~oicc for asteroid exploration with a single launch; and 5) them are more frequent launch opportunities.

The cm-rent mission objectives can be attained without an Earth-spiral escape operation.

7. ACKNOWLEDGEMENT '

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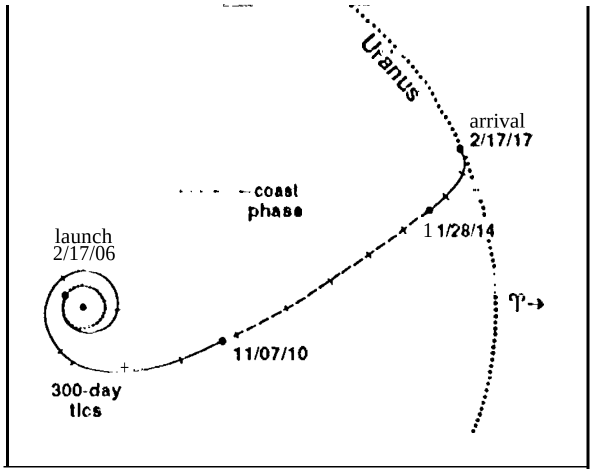


Fig. 3: *2006* Earth-Uranus Trajectory.

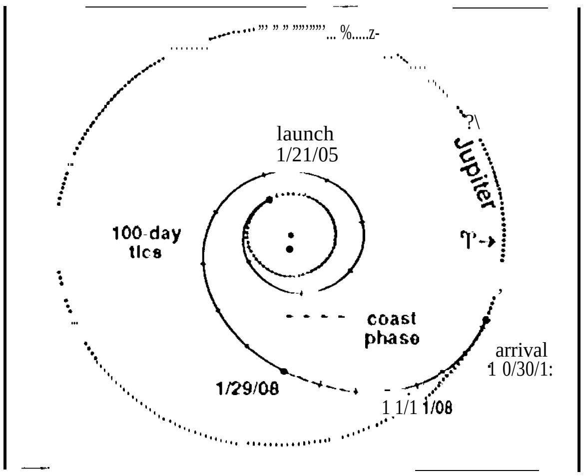


Fig. 6: 2005 Earth-Jupiter Trajectory

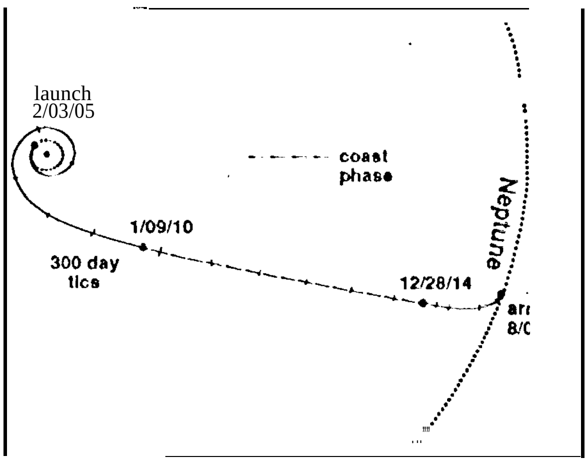


Fig. 4: 2005 Earth-Neptune Trajectory

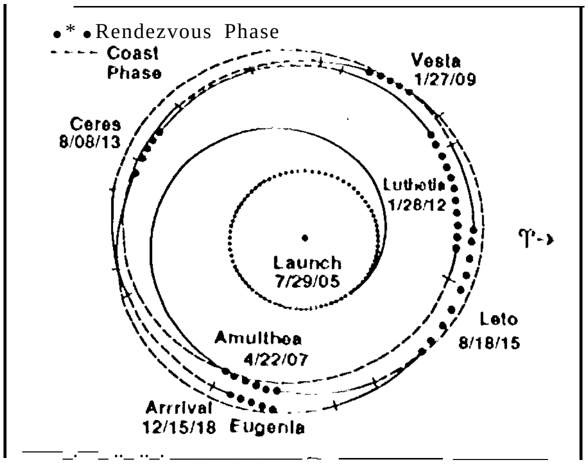
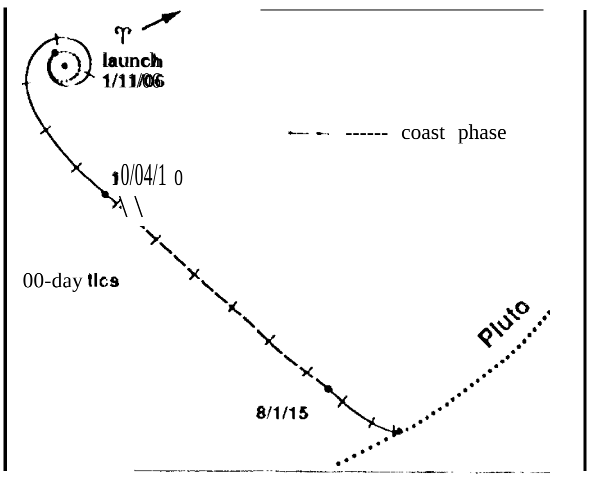


Fig. 7: Multiple Mainbelt Asteroid Rendezvous Trajectory



1 ig. 5: 2006 Earth-Pluto Trajectory

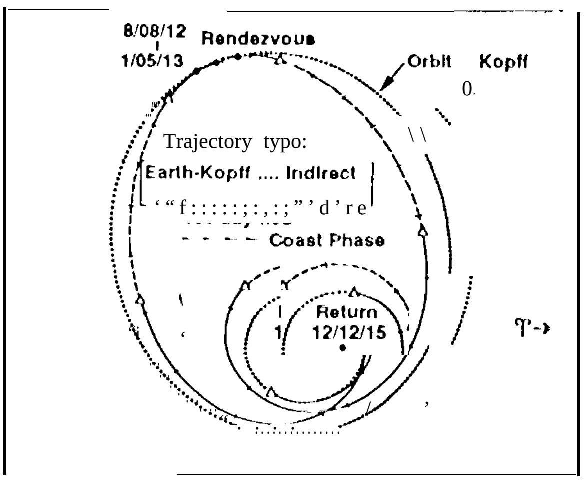


Fig. 8: 2008 Kopff Nucleus Sample Return Trajectory

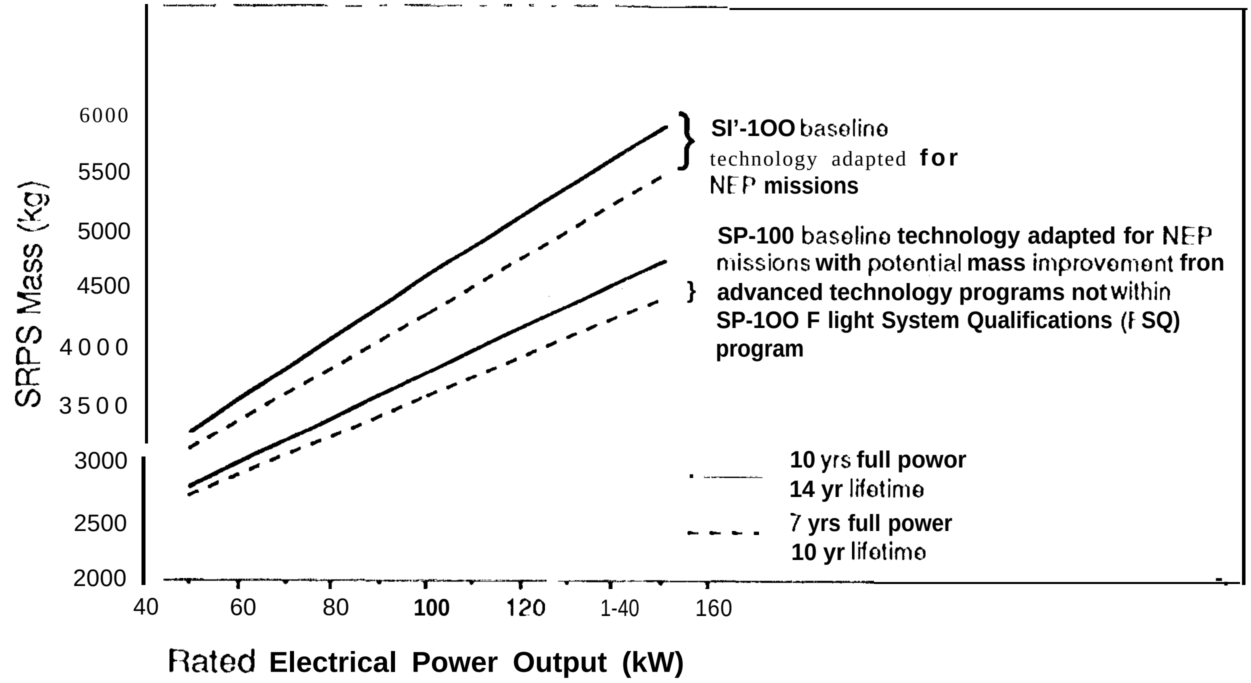


Fig. 1: Space Reactor Power System (SRI'S) Mass versus Power

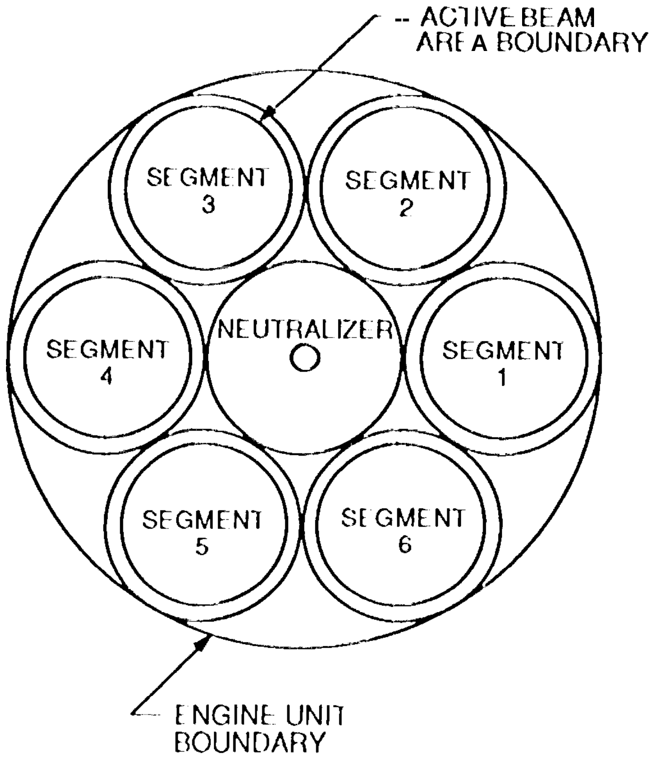


Fig. 2: Example of Segmented Engine configuration

"l'able 1. Baseline SP- 100 Technology Adapted for NEP Interplanetary Missions

- Deleted Armor for Protection Against Earth Orbital Debris
- Deleted Auxiliary Cooling Loop
- Jettison Reentry Heat Shield After Earth Escape
- Assumed End of Mission Reactor Coolant Temperature of 1400 K
- Mission Operating Time/Lifetime 7/1 O and 10/14 Years
- Thermoelectric Material Figure-of-Merit (Z) 0,85 $\times 10^{-3}$ K^{-1}
- User Plane Self-induced **Radiation 5** $\times 10^5$ rack (Gammas) and 1 $\times 10^{13}$ N/cm^2 (Neutrons)
- Radiator Density 8.74 kg/m^2 (Current SP-100 Design)
- Separation Distance 22 m
- Main Bus Voltage 200 V_{dc}

Table 2.' 30-cm Ring-cusp Thruster Performance Characteristics .

Isp (s)	Power Input to PPU (kW)	Total Efficiency (%)
5000	8.3	64
6000	10.0	67
7000	11.7	68
8000	13.3	69
9000	15.0	70
10000	16.7	70

Nomenclature for performance summary tables

FT	Heliocentric transfer time	N_I	Total no. of thrusters (ion sources) installed
FT1	Flight time including planetary spiral phase	N_{PPU}	No. of power processor units installed
VHL	Earth escape V_∞	MO	Launch mass minus adapter
P0	Input power to PPU	M_P	Propellant mass
ISP	Specific impulse	M_{PP}	SRI% mass
P_R	Thruster power rating	M_{TH}	Thrust subsystem dry mass (including tankage)
P_O	Operating power level of thruster	M_{NEP}	Total NEP system mass (dry)= ($M_{PP}+M_{TH}$)
T*,	Thruster life at operating power	M_{Pl},	Payload delivered to final orbit
Tp	Total propulsion time	V_{AC}	Total characteristic velocity of the mission
N_O	No. of operating thrusters in a unit cluster		

Table 3. Uranus Orbiter/Probe Performance Summary.

Requirements: Mn,>]410 kg (note: probe released from high altitude orbit-24 R_u)

UO/P with (Titan IV/Centaur +NEP)

FT (yr)	FT1 (yr)	VHL (km/s)	P0 (kw)	ISP (sec)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	NO	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	V_{AC} (km/s)
14.0	16.4	1.3	52	10000	17	13	1.47	12.1	4	44	2	8846	2828	2936	1116	4051	886	39.6
14.5	17.1	1.4	50	1000O	17	17	1.15	12.3	3	42	2	8811	2757	2895	1074	3969	1004	38.6
15.0	17.7	1.5	48	10000	17	16	1.19	12.5	3	42	2	8782	2694	2860	1054	3914	1093	37.8
15.5	18.3	1.5	46	10000	17	15	1.23	1?.6	3	39	2	8763	2642	2832	1012	3844	1196	37.0
16.0	18.9	1.6	45	10000	17	15	1.26	12.7	3	39	2	8757	2603	2810	999	3809	1264	36.4
16.5	19.5	1.5	44	10003	17	15	1.28	12.9	3	39	2.	8774	2584	2797	990	3787	1322	36.0
17.0	20.1	0.8	42	10000	17	14	1.36	14.8	3	42	2	9021	2814	282.5	1017	3841	1285	38.5
17.5	20.8	0.8	40	10000	17	13	1.41	15.2	3	42	3	9005	2774	2799	1165	3964	1186	37.9
18.0	21.4	0.9	39	10000	17	13	1.46	15.5	3	42	3	8985	2728	2774	1144	3919	1257	37.3

Comments:
- No acceptable performance for the proposed scenario.
- Less demanding mission might be considered.

UO/P with (HLV/Centaur +NEP)

FT (yr)	FT1 (yr)	VHL (km/s)	P0 (kw)	ISP (sec)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	N_o	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	V_{AC} (km/s)
10.0	11.4	1.9	99	8086	13	12	1.24	8.0	8	72	2	13511	5474	3704	1986	5689	1267	42.!
10.5	12.1	1.9	98	8365	14	14	1.14	8.3	7	70	2	13534	5231	3703	1936	5639	1583	41.4
11.0	12.7	1.9	97	8601	14	14	1.18	8.6	7	70	2.	13626	5071	3713	191-/	5630	1844	40.!
11.5	13.3	1.6	98	8831	15	14	1.20	8.9	7	70	2	13885	5045	3760	1921	5681	2078	40.3
12.0	13.9	0.8	101	9356	16	14	1.24	10.3	7	77	2	14588	5328	3942	2031	5973	2206	42.9
12.5	14.6	0.8	98	9752	16	14	.1.32	11.0	7	7’/	2	14590	5134	3952	1992	5944	2431	42.6
13.0	15.3	0.9	96	10093	17	16	1.20	11.6	6	78	2	14553	4913	3945	1961	5906	2653	41.9
13.5	16.0	0.9	94	10388	17	16	1.26	12.0	6	72	2	14510	4704	3931	1873	5805	2.920	41.1
14.0	16.6	1.0	92	10640	18	15	1.32	12.3	6	72	2.	14472	4521	3915	1841	5756	3114	40.2
14.5	17.3	1.0	90	10855	18	18	1.14	12.6	5	70	2	14451	4371	3901	1797	5698	3301	39.5
15.0	17.9	1.0	89	110S0	18	18	1.18	12.9	5	70	2	14460	4258	3896	1777	5673	3448	38.9
15.5	18.5	0.9	88	11274	19	18	1.21	13.4	5	70	2	14535	4200	3917	1767	5684	3570	38.8
16.0	19.2	0.6	88	11761	20	18	1.27	14.7	5	75	2	14712	4223	4012	1809	5821	3587	40,1

Comments:
Minimum flight time= 10.5 years, mission time - 12.5 years.
Can tolerate NEP mass uncertainty of 30 % @FT=14 years.
Non, inal P0~100kW, ISP~8500 sec.
Viable option

Table 4. Neptune C)rbitcr/?'robe Performance Summary

Requirements: M_{P1},214 10 kg (note: Neptune probe released on approach)

NEO/P with (Titan IV/Centaur + NEP)

FT (yr)	FT1 (yr)	VHL (km/s)	PO (kw)	ISP (See)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	NO	N_I	N_{PPU}	M. (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	'AC (km/s)
16.0	16.9	1.1	58	10000	17	14	1.31	11.6	4	48	2	8923	3035	3054	1219	4274	1238	41.0
16.5	17.5	1.2	56	10000	17	14	1.37	11.8	4	44	2	8901	2963	3010	1159	4170	1392	40.0
17.0	18.0	1.3	54	10000	17	13	1.42	11.9	4	44	2	8878	2891	2971	1137	4108	1503	38.9
17.5	18.6	1.3	52	10000	17	13	1.46	12.0	4	44	2	8856	2823	2936	1116	4052	1605	37.9
18.0	19.1	1.4	50	10000	17	13	1.51	12.1	4	44	2	8837	2760	2905	1099	4003	1698	37.0

. minimum flight time=17 years, total mission time -19 years.
. Practically no performance margin
• Not a viable)tion.

NEO/P with (HLV/Centaur +NEP)

FT (yr)	FT1 (yr)	VHL (km/s)	PO (kw)	Is P (sec)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	NO	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M * (kg)	M_{PL} (kg)	'AC (km/s)
11.5	12.0	1.9	102	7565	13	11	1.27	7.7	9	72	2	13548	6185	3741	2078	5818	1169	45.4
12.0	12.5	1.9	101	7826	13	13	1.17	7.9	8	7 2	2	13580	5901	3745	2046	5190	1513	44.0
12.5	13.1	1.9	101	8051	13	13	1.22	8.1	8	72	2	13623	5664	3746	2018	S163	1820	42,6
13.0	13.6	1.8	100	8248	14	12	1.25	8.3	8	7 2	2	13693	5477	3748	1996	5744	2096	41.S
13.5	14.1	1.7	100	8428	14	12	1.29	8.4	8	7 2	2	13813	5349	3760	1982	5142	2346	40.7
14.0	14.7	1.5	10 I	8637	14	14	1.14	8.8	7	70	2	14073	5331	3806	1970	5776	2590	40.5
14.5	15.2	0.8	102	9136	15	15	1.19	10.0	7	77	2	14592	5517	3949	2059	6007	2692	42,7
15.0	1S.8	0.8	100	9476	16	14	1.2s5	10.7	7	77	2.	14615	5358	3959	2026	5985	2896	42.6
15.5	16.4	0.8	98	9755	16	14	1.33	11.1	7	77	2	14599	5167	3953	1992	5944	3112	42.0
16.0	16.9	0.8	96	9996	17	16	1.19	11.5	6	78	2	145"/5	4978	3940	1968	5908	3313	41.1

, Minimum flight time=12 years, total mission time -14 years.
, Addition of a Triton lander possible @FT= 13.5 years, total mission time - 15.5 years.
, Can tolerate NEP mass uncertainty of 30 % @FT=15.5 years, but thrust time and mission time is longer.
Nominal PO ~ 100 kW, ISP ~8000 seconds.
Viable option

Table 5. Pluto Orbiter/P(optional lander) Performance S ummary

Requirements: $M_{PL} \geq 1410$ kg

PLO/P with (Titan IV/Centaur + NEP)

FT (yr)	FT1 (yr)	VHL (km/s)	Po (kw)	Is P (See)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	N_o	N_I	N_{PPU}	M 0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	V_{AC} (km/s)
13.5	13.5	2.4	58	8095	13	12	1.32	7.8	5	40	2	8315	3134	2844	1162	4006	1175	37.6
14.0	14.0	2.4	57	8238	14	11	1.37	7.9	5	40	2	8303	3009	2829	1143	3972	1322	36.4
14.5	14.5	24	56	8358	14	11	1.41	8.0	5	40	2	8301	2905	2815	1127	3942	1454	35.3
15.0	15.0	2.4	56	8461	14	14	1.15	8.0	4	36	2	8314	2822	2804	1079	3883	1609	34.4
15.5	15.5	2.3	55	8556	14	14	1.18	8.1	4	36	2	8351	2763	2800	1070	3870	1718	33.7
16.0	16.0	1.0	58	9390	16	15	1.22	10.3	4	44	2	8967	3075	2989	1192	4181	1711	38.7
16.S	16.5	1.0	57	9617	16	14	1.28	10.6	4	44	2	8952	2964	2980	1172	4152.	1836	37.9
17.0	17.0	1.1	56	9812	16	14	1.33	10.9	4	44	2	8931	2856	2968	1152	4120	1955	37.1
17.5	17.s	1.2	55	9979	17	14	1.38	11.1	4	44	2	8909	2755	2953	1134	4087	2067	36.2
18,0	18.0	1.2	54	10121	17	13	1.43	11.2	4	40	2	8887.	2662	2937	1083	4020	2205	35.3

. Orbiter is a NEP enabled mission mode.
. Minimum flight time=14.5 years, total mission time -16.5 years.
. Feasibility indicated but margin may not be sufficient.
. Nominal PO ~ 55 kW, ISP ~ 8400 sec.
• May be a viable and attractive option if mass growth in all components can be controlled.

l'able 5. Pluto Orbiter/P(optional lander) Performance Summary (continued)
Requirements: M_{PL},21410 kg

Pl .O/P with (HLV/Centaur +NEP)

FT (yr)	FTI (yr)	VHL (km/s)	P0 (kw)	1s}' (sec)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	N_o	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{T} (kg)	M_{NEP} (kg)	M_{PL} (kg)	‘AC (km/s)
11.0	11.0	1.8	103	6884	11	11	1.14	6.8	9	72	2	13659	6671	3682	2132	5813	1175	45.2
11.5	11.5	1.8	103	7157	12	11	1.19	7.0	9	72	2	13706	6337	3691	2097	5'/88	1581	43.6
12.0	12.0	1.8	102	7396	12	11	1.24	7.2	9	72	2	13734	6034	3691	20752	5753	1947	42.0
12.5	12.5	1.7	101	7602	13	13	1.15	7.3	8	64	2	13761	S170	3684	1961	5645	2346	40.5
13.0	13.0	1.7	100	7717	13	12	1.18	7.4	8	64	2	13798	5547	3675	1933	5608	2643	39.2
13.5	13.5	1.7	99	7929	13	12	1.22	7.5	8	64	2	13857	5368	3658	1910	5578	2911	38.1
14.0	14.0	1.6	99	8070	13	12	1.24	7.7	8	64	2	13955	5238	3659	1894	5563	3154	37.2
14.5	14.5	1.4	99	8245	14	12	1.27	7.9	8	64	2	14163	5197	3697	1894	5591	3375	37.0
15.0	15.0	0.8	100	8736	15	14	1.16	9.1	7	70	2	14610	5371	3826	1971	S197	3442	39.3
15.5	15.5	0.7	98	9077	15	14	1.23	9.7	7	70	2	14647	5240	3839	1941	5780	3627	39.4
16.0	16.0	0.7	96	9335	16	14	1.29	10.2	7	70	2	14638	5067	3831	1909	5740	3831	38.9

• Orbiter is a NEP enabled mission mode.
: Minimum flight time= 11.5 years, total mission time -13 years.
• Lander for both Pluto and Charon possible @FT=13.5 years, and mission time -15 years.
: Nominal P0 ~ 100 kW, ISP~ 7200 sec.
• Sufficient margin, valid option.

Table 6. Jupiter Grand Tour Performance Summary .
Requirements: $M_{PL} \geq$ 1434 kg (Excess performance arc for probes or for two JPO spat.e.craft)

JGT with (Titan IV/Centaur + NEP)

FT (yr)	IFTI (yr)	VH (km/s)	P0 (kw)	ISP (sCC)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	NO	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	V_{AC} (km/s)
4.50	7.5	2.3	62	7s19	13	12	1.16	6.6	5	40	2	8363	3232	2855	1205	4059	1072	36.3
4.75	8.2	2.3	60	8122	14	12	1.28	7.4	5	40	2	8340	3030	2857	1168	4025	1285	36.0
5.00	8.9	23	58	8653	14	12	1.41	8.2	5	40	2	8339	2S69	2864	1138	4003	1467	35.8
5.25	9.6	2.5	55	9164	15	14	1.26	8.9	4	36	2	8204	2654	2847	1061	390s	1612.	35.1
5.50	10.4	2.8	53	9650	16	13	1.39	9.6	4	36	2	8055	2463	2828	1022	3850	1742	34.5
5.75	11.1	2.9	50	10081	17	13	1.52	10.3	4	36	2	7919	2708	2811	988	3799	1812	34.1
5.00	11.7	3.1	49	10424	17	16	1.22	10.8	3	36	2	7823	2198	2801	964	3765	1860	33.7
.5.25	12.3	3.1	48	10655	18	16	1.27	11.2	3	36	2	?189	2138	2799	952	3-/50	1901	33,5
6.50	1?.6	3.1	48	10778	18	16	1.29	11.4	3	36	2	7820	2124	2807	949	3756	1940	33.5
6.75	12.9	2.9	48	10812	18	16	1.27	11.5	3	36	2	7920	2154	2826	957	3783	1983	33.7

. minimum flight time= 5 years, total mission time -10 years, spiral tune at Jupiter is long.
. Sate.llite orbiter [our (no additional payload) seem feasible, but margin is not large.
o Nominal PO ~ 60 kW, IS P- 8500 sec.
. Modest performance but science return is still significant.
‘ Tight control of mass growth is necessary to be valid.

Table 6. Jupiter Grand Tour Performance Summary (continued)
Requirements: $M_{PL} \geq 1434$ kg (Excess **performance** arc for probes or for two JPO **spacecraft**)

JGT with (HLV/Centaur +NEP)

FT (yr)	FT1 (yr)	VHL (km/s)	P0 (kw)	ISP (sec)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	N_o	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	V_{AC} (km/s)
3.25	7.1	5.8	48	8145	14	12	1.28	6.8	4	28	2	6971	2232	X87	895	3482	1257	30.!
3.50	7.6	5.7	49	8418	14	12	1.31	7.1	4	28	2	7142	2219	2615	S98	3513	1410	30.[illegible]
3.75	7.7	5.S	52	8347	14	13	1.21	7.0	4	32	2	7577	2385	2681	977	3658	1534	30.[illegible]
4.00	7.7	5.1	58	8143	14	12	1.34	6.8	5	35	2	8178	2658	2714	1072	3846	1674	31.4
4.2s	7.7	4.6	6.5	7845	13	11	1.35	6.4	6	3 6	2	9079	3103	2918	1190	4108	1868	32.2
4.50	7.4	1.6	104	7521	13	12	1.23	6.6	9	63	2	13891	5517	3692	1959	5651	2723	37.3
4.75	8.0	1.7	101	8018	13	13	1.21	7.3	8	64	2	13760	5131	3673	1900	5573	3056	36.7
5.00	8.7	1.9	97	8491	14	14	1.17	7.9	7	63	2	13600	4781	3649	1828	5477	3342	36.1
5.25	9.4	2.0	93	8918	15	13	1.27	8.5	7	63	2	13438	4486	3625	1772	5397	3555	35.5
5.50	9.9	2.1	91	9270	15	15	1.17	9 . 0	6	6 0	2	13327	4270	3609	1705	5314	3743	35.1
5.75	10.4	21	89	9525	16	15	1.2.2	9.3	6	60	2	13314	4150	3610	1682	5292	3872	34.9
6.00	1 0 , 8	2.0	89	9688	16	15	1.24	9.6	6	60	2	13421	4123	3631	1680	5311	3987	34.9
6.25	11.1	1.8	91	9772	16	15	1.23	9.8	6	60	2	13692	4203	3682	1701	5384	4105	35.1
6.50	11.3	0.9	97	9s09	16	16	1.15	10.1	6	66	2	14514	4602	3848	1841	5689	4223	36.7

. Minimum flight time≈3.5 years, total mission time ~10 years, spiral time at Jupiter is long.
. Longer FT (~5 years) may not be objectionable. Note the steep payload increase with FT. Case with longer 1'1" should be nominated because of increased science return
. More demanding mission wirh - two landers or two fields and particles spacecraft (totalling 2500 kg) is possible. at FT≈6 years.
, PO and ISP vary relatively widely with FT.
· Ample margin exists to perform a the basic mission.

Table 7. Multiple Mainbelt Asteroid Rendezvous (optional landers) Performance Summary
Requirements: $M_{PL} \geq 1395$ kg (Excess performance arc for penetrators)

MMBAR with (Titan IV/Centaur +NEP)

BODY	Earth	113-Amalthea	4-Vesta	21-Luthetia	1-Ceres	68-Leto	45-Eugenia
RENDEZVOUS DATE	7/29 2005	2/22 2007	1/27 2009	1/28 2012	8/08 2013	8/18 2015	12/15 2018
TYPE		SX	V	M	G	S	C
RADIUS		24	288	54	516	64	122

FT (yr)	FT1 (yr)	VHL (km/s)	Po (kw)	ISP (se.)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	N_o	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	V_{AC} (km/s)
13.4	13.4	2.9	40	5335	9	8	1.26	5,0	5	25	2	793 I	3185	2348	890	3238	1508	26.9

. Multiple rendezvous with highly desirable targets can be adequately accomplished with this system.
. Although mass margin is not indicated in the table, it may be obtained with alternative targets and longer FT or dropping one target
. Nominal P0≈40 kW, ISP≈5300 sec. (small compared to other missions)
. Thrust time is modest, but FT is long (on the average 2 years per target).
. Best mission for a first NEP application.

MMBAR with (HLV/Centaur +NEP)
Rendezvous Seqence and Performance.

BODY	Earth	4-Vesta	9-Metis	21-Luthetia	102-Miriam	1-Ceres	68-Leto
RENDEZVOUS DATES	1/07 2005	8/20 2007	[illegible] 2008	1/08 2010	5/31 2012	8/14 2014	1/19 2016
TYPE		V	S	M	C	G	S
RADIUS		288	79	54	45	516	64

FT (yr)	FT1 (yr)	VHL (km/s)	P0 (kw)	ISP (sec)	P_R (kw)	P_o (kw)	T_L (yr)	T_P (yr)	N_o	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	V_{AC} (km/s)
11.0	11.0	0.1	93	6023	10	9	1.23	6.3	10	70	2	14827	7307	3437	2088	5524	1996	40.1

· Performance improvement over Titan IV/Centaur + NEP case is not significant.
· Nominal P0 ≈ 90 kW, ISP ≈ 6000 sec.

Table 8. Comet Nucleus Sample Return Performance Summary

Example Missions

Comet	Launch Date	Comet Date	Earth Return Date
Tempel 2 (T2)	4/05/2005	9/20/'2 008	2/24/201 1
Tempel 2 (T2)	6/24/2004	8/26/? 008	2/24/2011
Tsuchinshan 2 (TS2)	11/03/2005	5/23/'2008	7/20/2012
Tsuchinshan 2 (TS2)	12/16/2004	12/0 1/2008	7/20/2012
Kohoutek (KOH)	8/29/2007	8/01/2010	5/31/2014
Kohoutek (KOH)	10/28/2006	11/13/2010	5/31/2014
Kopff (KOPF)	2/24/2009	7/19/'2012	1 2/20/2015
Kopff (KOPF)	5/19/2008	8/08/'2012	12/20/2015
Wild 2 (W2)	10/22/2009	3/05/'201 3	8L20/2016
Wild 2 (W2)	2/01/2009	3/22/2013	9/19/2016

Requirements: $M_{PL} \approx$ **1800** kg (note: **500** kg lander/sampler left **on** comet)

CNSR with (HLV/Centaur + NEP)

Comet	FT (yr)	VHL (km/s)	PO (kw)	ISP (sec)	P_R (kw)	P_o (kw)	T_L (yr)	T_p (yr)	N_o	N_I	N_{PPU}	M_0 (kg)	M_P (kg)	M_{PP} (kg)	M_{TH} (kg)	M_{NEP} (kg)	M_{PL} (kg)	ΔAC (km/s)
T2	5.9	26	86	4749	8	8	1.16	[illegible]	11	44	2	12651	5824	3353	1671	5024	1303	29.7
T2	6.7	0.8	92	4773	8	8	1.18	3.8	12	48	2	14589	6866	3476	18S1	5328	1895	30.6
TS2	6.8	3.1	83	452.5	8	8	1.14	2.7	11	33	2	11838	4994	3291	1475	4766	1578	25.2
TS2	7.6	0.9	96	5067	8	8	1.20	3.9	12	60	2	14559	6659	3562	1971	5533	1867	31.3
KOH	6.7	3.S	76	4560	8	7	1.25	2.7	11	33	2	10996	4513	3156	1376	4531	1452	24.6
KOH	7.6	0.8	95	5076	8	8	1>?2	3.9	12	60	2	14570	6548	3539	19s1	5491	2031	30.6
KOPF	6.8	2.4	91	4493	7	7	1.22	2.9	13	39	2	12884	5800	3450	,665	5115	,469	27.2
KOPF	7.6	0.9	94	4960	8	8	1.20	3.9	12	60	2	14562	6574	3521	1955	5476	1912	30.9
W2	6.8	2.0	95	4493	7	7	1.17	2.8	13	52	2	13464	6057	3540	1838	5378	1529	27.1
W2	7.6	0.8	94	4983	8	8	1.20	3.8	12	48	2	14567	6548	3525	1842	5367	2152	30.0

Comments:

- Direct and indirect class of trajectories are considered. The first entry for each target is the direct mode, and the 2nd the indirect.
- Indirect trajectory with FT of 6.7 to 7.6 years is required to satisfy the payload requirement.
- Nominal PO ≈ 95 kw, ISP ≈ 5030 dec.
- Performance margin will require longer FT and other classes of trajectories. To be investigated.
- Thrust time ≈ 4 years

Table 9. Summary of NEP System Design Parameters

Mission	UO/P	NEO/P	PLO/P	PLO/P	JGT
Lv	HLV	HLV	Titan IV	HLV	Titan IV
FT (yr)	10.5-14.	12-15	14.5	11.5-14	5 - 7
PO (kW)	98-92	101- 100	56	103-99	58-48
ISP (sec.)	8400 - 1 0000	7800-9500	8400	7200 - 8100	8700-10000
N_I	70- 78	72-77	40	7? -64	40-36
Tp (yr)	8.3 -12.3	7.9 -10.7	8.0	7.0 -7.7	8.2 - 11.5
Mission Time (yr)	14 -19	14.5- 18	16.5	13-16	12-15

Mission	JGT	MMBAR	MMBAR	CNSR
Lv	HLV	Titan IV	HLV	HLV
FT (yr)	5-6.5	13.5	11	6.7-7.6
PO (kW)	97-97	40	93	92-96
ISP Sec.)	8500- 9800	5300	6000	-5030
N_I	63-60	25	70	50-60
Tp (yr)	7.9- 10.	5	6.3	4.0
Mission Time (yr)	11 - 14	,13.5	11	8